WIND ENGINEERING
CONSIDERATIONS FOR
BRIDGE DESIGN

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Redefining possible.

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Rowan Williams Davies & Irwin Inc.
Introduction

JASON MUNN
Senior Project Manager | Associate
Email Jason

Jason Munn specializes in helping clients realize their vision for high-performance buildings and outdoor spaces. Jason’s technical knowledge and project experience give him the versatility to work across several of our service lines, managing project teams to produce a diverse range of structures with equally diverse functions. Jason delivers exceptional value in our innovative work with sports facilities; he has a strong record of leveraging the unique qualities of each project’s local microclimates to optimize the stadium experience for fans and athletes alike.

PIERRE-OLIVIER DALLAIRE
Technical Director | Principal
Email Pierre-Olivier

Pierre-Olivier has contributed engineering work to prominent bridge projects around the world. With a background in mechanical engineering and extensive experience in developing advanced numerical modeling techniques to support safe and efficient bridge designs, Pierre-Olivier is an asset to any design team. In addition to his project work on numerous long-span bridges, he has performed structural wind load studies on other structures subject to serious wind effects, including chimneys and tall buildings.

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A skilled project manager with a specialty in aligning structures with local microclimates

EDUCATION
- Bachelor of Science (Engineering) (Hons.), Queen’s University, Canada

AFFILIATIONS
- Professional Engineer (P.Eng.), Ontario
- Ontario Society of Professional Engineers (OSPE)
- Project Management Institute (PMI)

SPECIALTIES
- Air quality
- Building performance
- Cladding/structural wind loading
- Client engagement
- Noise and vibration
- Pedestrian wind
- Sports venues

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A talented engineer specializing in bridge aerodynamics and structural wind load studies

EDUCATION
- Master of Science (Mechanical Engineering), Université de Sherbrooke, Canada
- Bachelor of Engineering (Mechanical Engineering - Aeronautics)

AFFILIATIONS
- Professional Engineer, Quebec
- Numerous publications in technical journals

SPECIALTIES
- 3D flutter assessments
- Aeroelastic models
- Bridge aerodynamics
- Bluff-body aerodynamics
RWDI - Consulting Engineers & Scientists

600+ employees

Multi-disciplinary teams
  • Senior scientists; engineers; specialists; meteorologists; engineering technologists; technicians; support staff

International reputation

Exclusive methods and equipment
Overview – Bridge Performance

1. Wind climate
   (historical data & topographical assessment)

2. Aerodynamic stability and wind loads
   (sectional and aeroelastic tests, CFD, time domain buffeting simulation)

3. Wind barriers
   (user comfort, aerodynamic performance, ice accretion)

4. Traffic, comfort and damping
   (other sources of vibration, controlling vibrations)

5. Cable vibrations
   (aerodynamic & damping considerations)
Learning Objectives

1. To understand vibration effects and dynamic loading on long span bridges due to wind.

2. To discuss how to model the sources of vibrations and to predict the bridge responses numerically.

3. To understand how to mitigate theses vibrations using shape modifications or external devices.

4. To appreciate the advantages of wind tunnel testing to prevent undesired responses of the structure.

5. To understand an advanced way of analyzing pedestrian-induced vibrations.
WIND CLIMATE AND SITE ANALYSIS
Objectives of Wind Climate Study

• To establish the site-specific wind speeds for aerodynamic stability and wind loading

• To determine the directionality of the local winds

• To assess the approaching wind profiles and turbulence properties
Making use of **Historical Data**: Translating Wind Speeds from Weather Station to Site

The upwind terrain at the weather station influences the wind speed profile differently than at the bridge site, up to gradient height, $v_g$, the height beyond which the surface roughness has any influence on the wind speed or turbulence. The ESDU method calculates the wind speed profile based on the changes in the upwind terrain and their relative distance to the measurement location, up to gradient height. The gradient height wind speed can then be similarly scaled down to the bridge deck height based on the upwind terrain at the bridge site.
Golden Gate Bridge Site
Wind Speed vs Return Period

- Oakland International
- Naval Air Station Alameda
- San Francisco International
Wind Speed vs Return Period
Directionality of Extreme Winds
# Example of the Outcome of a Wind Climate Site Analysis

**Recommended wind speeds at bridge site**

<table>
<thead>
<tr>
<th>Wind Speed Applicable for</th>
<th>Return Period (years)</th>
<th>Mean Wind Speed (mph) at Deck Level 254 ft and Averaging Time</th>
<th>Corresponding 3-second Gust Speed (mph) at C 33 ft Open Terrain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design during construction</td>
<td>20</td>
<td>65.1</td>
<td>72.5</td>
</tr>
<tr>
<td>Design of completed bridge</td>
<td>100</td>
<td>74.2</td>
<td>82.7</td>
</tr>
<tr>
<td>Stability during construction</td>
<td>1,000</td>
<td>87.3*</td>
<td>96.5*</td>
</tr>
<tr>
<td>Stability of completed bridge</td>
<td>10,000</td>
<td>100.4*</td>
<td>111.0*</td>
</tr>
</tbody>
</table>

**Turbulence properties at deck level of 254 ft**

<table>
<thead>
<tr>
<th>Direction (°CW from N)</th>
<th>$z_o$ (ft)</th>
<th>$\alpha$</th>
<th>$I_u$ (%)</th>
<th>$I_v$ (%)</th>
<th>$I_w$ (%)</th>
<th>$xL_u$ (ft)</th>
<th>$xL_w$ (ft)</th>
<th>$yL_u$ (ft)</th>
<th>$yL_w$ (ft)</th>
<th>$zL_u$ (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>270</td>
<td>0.016</td>
<td>0.126</td>
<td>11.2</td>
<td>8.8</td>
<td>6.2</td>
<td>1523</td>
<td>128</td>
<td>430</td>
<td>72</td>
<td>274</td>
</tr>
<tr>
<td>90</td>
<td>0.033</td>
<td>0.134</td>
<td>12.1</td>
<td>9.5</td>
<td>6.7</td>
<td>1603</td>
<td>134</td>
<td>451</td>
<td>76</td>
<td>286</td>
</tr>
</tbody>
</table>
Complex Environment

Effects of topography:

• Increasing the speed of oncoming winds (funnelling)
• Redirecting winds (steering)
• Changes in turbulence
Complex Environment

Detailed topography tests:
Complex Environment
Meteorological Assessment

**Extreme wind events**
- Historical data
- Hurricane models
- Site data if available
- Numerical modeling (WRF)

**Wind turbulence at the site**
- Semi-empirical ESDU based predictions
- Topographic model studies

**Correlate predictions with site measurements**
- Installation, setup and monitoring of meteorological station at the site
- Statistical analysis to confirm semi-empirical predictions

**Ice and Snow**
AERODYNAMIC STABILITY AND WIND LOADING
Aerodynamic Instabilities

**Vortex-Induced Oscillations**: are self-limiting vibrations caused by the alternate and regular shedding of vortices from both sides of a bluff body, such as the bridge deck. These types of vibrations can be tolerated provided their amplitudes, and associated accelerations, do not exceed recommended thresholds.

**Galloping**: is a type of instability that is rarely found, and typically only on narrow bridge decks. Due to a negative rate of change in lift as the angle of attack increases, the section may start to move vertically across-the-flow to very large amplitudes.

**Flutter**: is a self-excited aerodynamic instability that could grow to very large amplitudes in torsional motion only, or into coupled torsional and vertical motions. Flutter instability should be avoided at all costs since it can lead to bridge failure.
Background

Vertical motions

Vortex-induced oscillations

Galloping – Negative aerodynamic damping
Background

Torsional motions

Vortex-induced oscillations

Flutter – Negative aerodynamic damping

Wind speed

Torsional response
Vertical (and torsional) motions

Turbulent buffeting response

Applied wind force
Experimental Methods

- Model-scale testing
  - Sectional Model Test (2D)
  - Force Balance Test (3D)
  - Aeroelastic Model Test (3D)
  - Speciality Model Test (snow, ice, vehicle overturning)

- Full-scale testing
  - Wind Measurements
  - Identification of Structural Dynamics Properties
  - Response Monitoring & Performance Testing
Sectional Model Test
Sectional Model Tests

Similarity requirements

\( \lambda = \text{Scale} \)

- \((\text{Mass/Length})_{\text{Model}} = (\text{Mass/Length})_{\text{Full Scale}} / \lambda^2\)
- \((\text{MMI/Length})_{\text{Model}} = (\text{MMI/Length})_{\text{Full Scale}} / \lambda^4\)
- \(\text{Speed}_{\text{Model}} = \text{Speed}_{\text{Full Scale}} \cdot \left( \frac{\text{Frequency}_{\text{Model}}}{\text{Frequency}_{\text{Full Scale}}} \right) / \lambda\)
- \((\text{Frequency}_{\text{Torsion}}/\text{Frequency}_{\text{Vertical}})_{\text{Model}} = (\text{Frequency}_{\text{Torsion}}/\text{Frequency}_{\text{Vertical}})_{\text{Full}}\)
- \(\text{Structural Damping}_{\text{Model}} = \text{Structural Damping}_{\text{Full}}\)
Experimental Wind Tunnel Study – Sectional Model Testing

- Sectional model tests at scale 1:60
- Free-vibration testing, force coefficients and aeroelastic coefficient extraction
- Results scaled for the lowest vertical and torsional modes of vibration
Experimental Wind Tunnel Study – Construction Configurations

Staging Configuration 1
- Two platforms

Staging Configuration 2
- Two platforms
- Tarp on the upper

Staging Configuration 3
- Two platforms
- Tarp on the lower

Staging Configuration 4
- Two platforms
- Tarp covering the full depth

Staging Configuration 5
- One platform

Staging Configuration 6
- One platform
Sectional Model Test, Case Study #1

Without guide vane

With guide vane

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Sectional Model Test, Case Study #2

Without deflector plate

With deflector plate
Sectional Model Test, Twin Bridges

Interference effects between bridges

Effects of traffic on aerodynamic stability
Preliminary Evaluation Using CFD

Understand the flow patterns

Identify possible instabilities

Evaluate mitigations and their effects on the flow

Estimate the mean forces (drag, lift and moment)
Aeroelastic Model Tests
Aeroelastic Modeling Principles

- \((\text{Mass/Length})_{\text{Model}} = (\text{Mass/Length})_{\text{Full Scale}} / \text{Scale}^2\)
- \((\text{MMI/Length})_{\text{Model}} = (\text{MMI/Length})_{\text{Full Scale}} / \text{Scale}^4\)
- \(\text{EA}_{\text{Model}} = \text{EA}_{\text{Full Scale}} / \text{Scale}^3\)
- \(\text{EI}_{\text{Model}} = \text{EI}_{\text{Full Scale}} / \text{Scale}^5\)
- \(\text{GJ}_{\text{Model}} = \text{GJ}_{\text{Full Scale}} / \text{Scale}^5\)
- \(\text{Speed}_{\text{Model}} = \text{Speed}_{\text{Full Scale}} / (\text{Scale})^{1/2} \) (Froude scaling law)
- \(\text{Frequency}_{\text{Model}} = \text{Frequency}_{\text{Full Scale}} \ (\text{Scale})^{1/2}\)
- \(\text{Structural Damping}_{\text{Model}} = \text{Structural Damping}_{\text{Full}}\)
Aeroelastic Model Tests

- Integrates a spine system for stiffness of the structure with shells for mass and aerodynamic shapes
- Boundary conditions simulated with appropriate flexure systems
- Finite element model analysis is typically used to confirm the frequencies and modes
Aeroelastic Model Tests

Ambassador Bridges
Aeroelastic Model Tests

St. Croix Crossing  Hastings Bridge
### Table 1: Modified Existing Bridge

<table>
<thead>
<tr>
<th>Mode #</th>
<th>Mode Shape</th>
<th>Measured Model Scale Frequencies (Hz)</th>
<th>Target Value from FEM (Hz)</th>
<th>% Difference</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1\textsuperscript{st} Lateral</td>
<td>1.0</td>
<td>1.03</td>
<td>-3%</td>
<td>0.35%</td>
</tr>
<tr>
<td>2</td>
<td>1\textsuperscript{st} Vertical</td>
<td>2.13</td>
<td>2.19</td>
<td>-3%</td>
<td>0.5%</td>
</tr>
<tr>
<td>4</td>
<td>2\textsuperscript{nd} Lateral</td>
<td>2.56</td>
<td>2.56</td>
<td>0%</td>
<td>NM</td>
</tr>
<tr>
<td>9</td>
<td>1\textsuperscript{st} Torsional</td>
<td>4.94</td>
<td>4.94</td>
<td>0%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

### Table 2: Proposed Bridge

<table>
<thead>
<tr>
<th>Mode #</th>
<th>Mode Shape</th>
<th>Measured Model Scale Frequencies (Hz)</th>
<th>Target Value from FEM (Hz)</th>
<th>% Difference</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1\textsuperscript{st} Lateral</td>
<td>1.39</td>
<td>1.49</td>
<td>6%</td>
<td>0.2%</td>
</tr>
<tr>
<td>2</td>
<td>1\textsuperscript{st} Vertical</td>
<td>1.84</td>
<td>1.74</td>
<td>5%</td>
<td>0.4%</td>
</tr>
<tr>
<td>3</td>
<td>2\textsuperscript{nd} Vertical</td>
<td>2.31</td>
<td>2.25</td>
<td>2%</td>
<td>NM</td>
</tr>
<tr>
<td>5</td>
<td>2\textsuperscript{nd} Lateral</td>
<td>3.49</td>
<td>3.58</td>
<td>-2%</td>
<td>NM</td>
</tr>
<tr>
<td>20</td>
<td>1\textsuperscript{st} Torsional</td>
<td>6.0</td>
<td>6.36</td>
<td>-6%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
Buffeting Analysis and Derivation of Wind Loads
Buffeting Analysis in the Time Domain

1. The structural model is simplified to a series of “strips”
2. A time series of turbulent wind is simulated based on the targets provided by the climatic conditions analysis
3. Appropriate aerodynamic properties, i.e., force coefficients, are assigned to each “strip”
Evaluating the Buffeting Motion to Derive Wind Loads

Dynamic information from design team (frequencies, modes, mass distribution)

Local wind climate parameters (wind speed, turbulence, wind profile)

Cross-section aerodynamic properties (shape, mean forces)

Compute numerically the structural response to fluctuating wind forces
Evaluating the Buffeting Motion to Derive Wind Loads
**Wind Loads**

Based on the simulations, peak displacements are identified and loading envelope established

Example: positive lateral and positive vertical displacements (x30)

**Modal participation factors**

\[
\{\hat{F}\}_{WL,i} = \bar{c}\{\overline{F}\} + [\hat{c}]_{BG}\{\hat{F}\} + c_{1,i}\{\hat{F}\}_1 + c_{2,i}\{\hat{F}\}_2 + \ldots + c_{m,i}\{\hat{F}\}_m,
\]
Equivalent Static Wind Loads

Cases are developed to capture the envelope of peak displacements

Example a) load case to capture uplift at mid span
Equivalent Static Wind Loads

Cases are developed to capture the envelope of peak displacements

Example b) load case to capture downforce at mid span

Displacement x 30
Aeroelastic Model Tests, Comparison with Wind-Induced Buffeting Analysis

The buffeting response is simulated to duplicate the aeroelastic model test conditions (in blue)

Deflections at key points along the bridges will be compared against the analytical buffeting predictions (in red)
Stability and Wind Loads – Summary

- Crucial to consider local topographic effects (if any) as well as local climate parameters (turbulence, icing of fences, etc.)
- Simple modifications to the cross-section can largely improve the aerodynamic performance (deck furniture, deflectors, shape changes)
- Wind loads can be reduced with these modifications, affecting the foundation design
- ... working hand in hand with the design team and architect to integrate these changes is key to success
WIND BARRIERS
Deck safety equipment

- Media divider
- Traffic and pedestrian barriers
- Wind barriers
- Suicide deterrent fences
Sectional model tests

Golden Gate Bridge
Existing deck cross-section

Golden Gate Bridge
Directionality

Graph showing wind directionality with different wind categories and alignment data.
Sectional model test
Recent Trends in North America

- Traffic barriers
Tsing Ma Bridge in Hong Kong

Storebaelt Bridge in Denmark
Tappan Zee Bridge
Tarry Town, NY
Case Study #1: Inset Barriers

FT-Solid barrier
approximately 1.5 m from leading edge

TF-2, half solid barrier
approximately 1.5 m from leading edge

#1 Deck width $B = 26.5\, m$
Full scale free vibration response, two different barriers
Significant VIO, flutter not an issue
Wind barriers

• Millau Viaduct
The Millau Viaduct - France
Wind Sheltering

Criteria:
- To maximize sheltering for traffic:
  - 40% reduction of gust wind speed, 3 m above deck
- To maintain aerodynamic stability
- To minimize increase in wind loading
- Hard to climb
Millau Wind Barriers

- 5 bars, C cross-section, 0.3 m wide, 0.3 m spacing
- 3 m overall height
- Translucid
- No aerodynamic tone
Assembled in situ
Suicide Deterrent Fences

• Angus Macdonald Bridge
The Angus Macdonald Bridge – Halifax, Canada

Means restriction fences
- Not climbable
- Bridge aerodynamically stable
Vortex-shedding induced vibrations of components of the fences
Vortex-shedding induced vibrations of components of the fences
Fences in the RWDI 24 ft wide Irwin Wind Tunnel
Estimation of Annual VIO cycles

1. Local wind climate
   - Joint probability of wind speed and direction, $P(\theta, U)$

2. Experiment
   - Test at wind angle, $\theta$

3. Rainflow cycle counting at each wind speed, $U$

4. Annual hours spent at each wind speed and direction

5. Cycle counts as a function of $f(\theta, U)$

6. Total cycles per year
Suicide Deterrent Fences

- Icing issues
Porosity

Ice accretion on chain link fences

Porosity 93%

6 mm of ice accretion

Porosity 50%

Porosity decrease

Full scale climatic wind tunnel testing of safety fences to determine ice accretion patterns
Effect of accretion on the porosity for two typical fence designs
Sectional Model Tests

Three different levels of porosity are used to establish critical flutter speeds
Wind Barriers

• Blow over study
Vehicle Blow Over Study in the Wind Tunnel
Vehicle Blow Over Study

Lift and yaw

Side force and pitching moment

Drag and roll

Vector diagram of speeds
Vehicle Blow Over Study

b) Results for Lower Deck

90 deg.

: Outside Lane

90 deg.

: Middle Lane

90 deg.

: Inside Lane
TRAFFIC, COMFORT, AND DAMPING
Strategy for Traffic-induced Vibrations and Comfort

**Comfort:** adopt comfort criteria (with design team & owner)

**Traffic scenarios:** define bridge usage (activities) and potential crowd sizes to evaluate

**Analytical estimates:** assess a certain number of scenarios for which the peak accelerations are predicted along the bridge

**Mitigation & refinements:** for unacceptable level of accelerations, evaluate the effects of a) structural modifications or b) supplementary damping systems
Walkers can Synchronize

Opening of the Millennium Bridge

The bridge was closed for 9 months

Tuned mass dampers and viscous dampers were installed to mitigate the motion
Comfort is Subjective

Summary of a variety of sources

Considerations:

• Peak accelerations
• Degree of freedom (vertical and lateral)
• Activity type
Pedestrian Loading

Final selection - different activities at various frequencies produce different loading
Crowd Walking Scenarios

<table>
<thead>
<tr>
<th>Density</th>
<th>Traffic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 people</td>
<td>Very weak</td>
<td>Day-to-day</td>
</tr>
<tr>
<td>0.2</td>
<td>Weak</td>
<td>Comfortable</td>
</tr>
<tr>
<td>0.5</td>
<td>Dense</td>
<td>Overtaking difficult</td>
</tr>
<tr>
<td>1.0</td>
<td>Very dense</td>
<td>Overtaking impossible</td>
</tr>
<tr>
<td>1.5</td>
<td>Exceptionally dense</td>
<td>Opening day, festival, etc.</td>
</tr>
</tbody>
</table>

1. Density is given in person/10 ft²
2. Images from:
   JRC 53442 Design of Lightweight Footbridges for Human Induced Vibrations
Forces Exerted While Walking
Time Domain Simulation

Displacements x25
Tuned Mass Dampers

TMDs are also used in relatively light bridges

\[ m_{TMD} \]

\[ m_{bridge} \]
Tuned Mass Damper, example
Tuned Mass Damper, example

2 x 2 TMD masses
Time Domain Simulation with TMDs

Displacements x25
Installation and Commissioning

Various activities were performed to ensure the effectiveness of the TMD
Equestrian Forces, Walking Activity
Time Domain Simulation, Equestrian Scenario with Tuned Mass Dampers
CABLE VIBRATIONS
Aerodynamics of Cables

Power imparted by the wind must be dissipated

- mass, damping, noise, friction, impact, cable oscillations, tower excitation

mass – damping = Scruton number

\[ S_c = \frac{m\zeta}{\rho D^2} \]

response to wind \( \propto \frac{1}{aS_c^{(b)}} \)
Aerodynamics of Cables

Excitation mechanisms:

• Vortex-shedding
• Rain-wind induced vibrations
• Buffeting due to turbulence
• Dry inclined cable galloping
• Ice accretion galloping
• Parametric excitation
Aerodynamics of Cables

Flow visualization, vortex shedding on a circular cylinder

Vertical motion caused by resonance
Strategy for Cable Vibrations

**Design**: to asses the damping demands to mitigate wind-induced vibrations

✓ To estimate the cable natural frequencies
✓ To evaluate critical speeds and damping demands for vortex shedding, galloping and rain-induced vibrations
✓ To account for possible ice accretion if appropriate

**In-service**: to evaluate the performance
✓ To confirm the cable damping through in-situ measurements
Cable Vibrations, case study

- Persistent vibrations for modest winds, for 5 years
- Multiple modes of vibration excited for all cables
- Damping demands were not defined at the design stage
Cable Vibrations, case study

• Structural failure due to fatigue

Typical cable diaphragm plate

Plate fracture
Monitoring for Diagnostics

• Cable vibrations due to wind or pedestrian or traffic induced?
  • 6-month monitoring
  • wind speed and direction
  • accelerometers on cables
  • data acquisition system at the base of the tower
  • automatic report, weekly, by phone

• Clear conclusion: vortex-shedding excitation of the cables
Cable Vibrations, case study

- An economic damping solution was evaluated (impact damper)

- Monitoring and full-scale forced vibration measurements were carried out to confirm the performance of the dampers
Evaluating Cable Performance
Evaluating Cable Performance
Recap

Wind tunnel tests, combined to advanced analytical modelling:
- are used to support the design team
- to ensure that the designers’ vision is realized with minimum compromise
- maximum service life, minimum operating costs, maximum performance.
Aerodynamics Throughout Lifecycle

- Geoscience services
- Aerodynamic (wind) studies
- Traffic noise

- Aerodynamic (wind) studies
- Cable vibration
- Damping systems

- Aerodynamic (wind) studies
- Noise & vibration
- Gust forecasting
- Monitoring (bridge & dampers)

- Damping systems
- Weather forecasting
- Cable Snow & Ice Accretion Monitoring

Planning
Design
Rehabilitation
Construction
Operation

Bridge
THANK YOU FOR YOUR TIME QUESTIONS?

Redefining possible.

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